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TOPEX/POSIEDON Autonomous Maneuver Experiment (TAME) Design and Implementation

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The need for higher level of spacecraft autonomy is gaining increased importance in future space missions planning, Future space missions will continue to be scientifically and technically more ambitious, and will demand more autonomy to accomplish complex tasks in uncertain environments and in close proximity to terrestrial bodies. In addition to mission demands, affordability is now a primary driver. The call is for smaller missions with greatly reduced ground control and operation. Spacecraft with highly autonomous, goal directed control systems would be required to meet these challenges. It is believed that the autonomy in addition to reducing the mission operations cost, will enable science objectives not possible using the current spacecraft architectural designs. Autonomous maneuver planning and implementation is one the key candidate technologies identified for such missions.

This paper describes the design and the implementation of an autonomous maneuver experiment. The experiment will provide proof of concept technology for an important area of on- board autonomy. TOPEX/POSIEDON Autonomous Maneuver Experiment (TAME) will provide the necessary algorithm for autonomous planning of constraint free attitude maneuvers to execute an Orbital Maintenance Maneuver (OMM). Currently the experiment is scheduled for June 1997. This paper will describe TAME's architecture, its planner algorithm and the design of the software.

INTRODUCTION

The need for higher level of S/C autonomy is gaining increased importance in future space missions' planning[1], Future space missions will continue to be scientifically and technically more ambitious, and will demand more autonomy to accomplish complex tasks in uncertain environments and in close proximity to terrestrial bodies. In addition to mission demands, affordability is now a primary driver. The call is for smaller missions with greatly reduced ground control and operation. Spacecraft with highly autonomous, goal directed control systems would be required to meet these challenges. It is believed that the autonomy in addition to reducing the mission operations cost, will enable science objectives not possible using the current spacecraft architectural designs. Autonomous maneuver planning and implementation is one of the key candidate technologies identified for such missions.

This paper describes the design and the implementation of an autonomous maneuver experiment. The experiment will provide proof of concept technology for an important area of on-board autonomy. TOPEX/POSIEDON Autonomous Maneuver Experiment[2] (TAME) will provide the necessary algorithm for autonomous planning of constraint free attitude maneuvers to execute an Orbital Maintenance Maneuver (OMM). Currently the experiment is scheduled for June 1997. This paper will describe TAME's architecture, its planner algorithm and the design of the software. TAME's main module is a planning engine (hat along with its auxiliary modules and a database will reside on an existing satellite processor. The database contains certain satellite and orbit constants as well as the tables of mission constraints. Upon receiving an OMM command, TAME will request up to date thermal and ephem eris data from the satellite's main computer (OBC). It will then initialize the planner module to design a constraint free attitude maneuver plan. The TAME planner algorithm generates paths that avoid geometric, power and thermal constraints. Another module, the sequence generator module, will then incorporate the generated path into an Orbit Maintenance Maneuver (OMM) sequence that would be void of other types of constraints such as command orders and timing. The generated command sequence, which will include the necessary commands to reconfigure and to condition the satellite and its components, will then be transferred to the OBC for activation.

This technology demonstration will provide data (o perform cost/benefits analysis to determine the proper trades between flight-and ground-based spacecraft mission operation. It will also provide approaches for the new paradigms in system architecture, ground commanding and test and verification that will be necessary for highly autonomous event-driven controls.

TOPEX/POSEIDON MISSION

The '1'OPliX/Poseidon Satellite, herein referred to as TOPEX (Ocean Topology Experiment) was launched on August 1 (), 1992, from the Kourou Space ~.enter in French Guyana. The satellite was launched into a nominal circular orbit with an altitude of 1336 Km and an inclination of 66 degrees. The TOPEX is a remote sensing mission with the primary science objective of providing sea surface alt i met ry from space[3]. The TOPEX/Poseidon program is jointly sponsored by The National Aeronautics and Space Administration (NASA) and Centre National d'Etudes Spatiales (CNES). This joint U.S./French mission combines each country's space wean research missions. The TOPEX mission is managed by the Jet Propulsion Laboratory (JPL) for the NASA office of Space Sciences Application. JPL, is also responsible for the day to clay operation of the satellite. The Poseidon is managed by the Toulouse Space laboratory for CNES. TOPEX was slated for a prime mission of three years, which was completed in September 1995. A three years' extension to the. mission has been approved by NASA.

The primary science objective of the TOPEX satellite is to provide highly accurate measurements of the sca sLu'face elevation over all of the ocean basins. The primary science requirement is to provide geocentric measurement of the global ocean sea level accurate to ± 14 cm with a precision of ± 2.4 cm along track. These requirements necessitated a frozen orbit that provides a fixed ground track every 10 sidereal days (127 o rbits)[4]. To maintain the frozen orbit, the satellite occasionally performs small burns referred to as Orbit Maintenance Maneuver (OMM).

TAME OBJECTIVE

It is the objective of TAME to develop the software that provides the capability for autonomous on-board planning and execution of an OMM. Orbit Maintenance Maneuver (OMM) is a multi-discipline activity. It may be best described by dividing the activity into three phases, the planning phase, the implementation phase and the execution phase. Planning phase is a navigation team activity that includes orbit determination, orbit control and orbit propagation functions to calculate the required ΔV vector. The implementation activity converts the request for a maneuver into a sequence of low-level satellite commands that will be uploaded to the satellite for execution. Currently, all of these functions are performed on the ground. Figure 1 summarizes the current TOPEX maneuver implementation activity.

In a fully autonomous approach all activities are performed on-board without any ground intervention. Although technically feasible for most modern day satellites, this level of autonomy was deemed as inappropriate for TAME. TOPEX on-board computers, the OBC and the GPS 1750A, simply do not have sufficient unused capacity to support completely autonomous maneuver functions. Since the execution phase of an OMM is performed autonomously by the satellite, it was decided that the next logical step in the autonomy would be to convert the implementation phase to all autonomous operation. Therefore in TAME the planning phase will remain a ground activity. Figure 2 shows the TAME implementation.

TAME ARCHITECTURE

OBC limitations and the safety of an on-going scientific mission require use of a second computer for the TAME implementation. An architecture has been developed that utilizes the **existing** TOPEX GPS experiment 1750A computer'. Under this architecture, TAME software loaded on the 1750A computer generates a sequence of commands functionally similar to the ground generated OMM command sequence. This sequence will then be transferred to the OBC for execution. The OBC will utilize existing maneuver routines to execute the experiment. Figure 3 shows TAME's modular block diagram while its data flow diagram is shown in Figure 4.

At the heart of the process is the Attitude Maneuver Planner module. The input to the **planner is** the required ΔV vector and allowable maneuver windows. Other inputs required by the planner are provided utilizing one of the following methods:

- Constraints and other parameters of importance, such as the thresholds and the desired set of the thrusters, will be resident in the appropriate on-board **databases.**
- 1750A resident software modules, **Sun and spacecraft ephemeris modules,** will propagate the spacecraft and the solar ephemerides, TAME will query the OBC for initial values..
- **Mathematical models** provide the spacecraft characteristics for the appropriate subsystems, such as the **Attitude Control Subsystem, Propulsion Sub-**

system, Power Subsystem and Thermal Subsystem, TAME will query the OBC for the required initial values.

- Up to date spacecraft state will be provided via the telemetry feedback from the OBC.

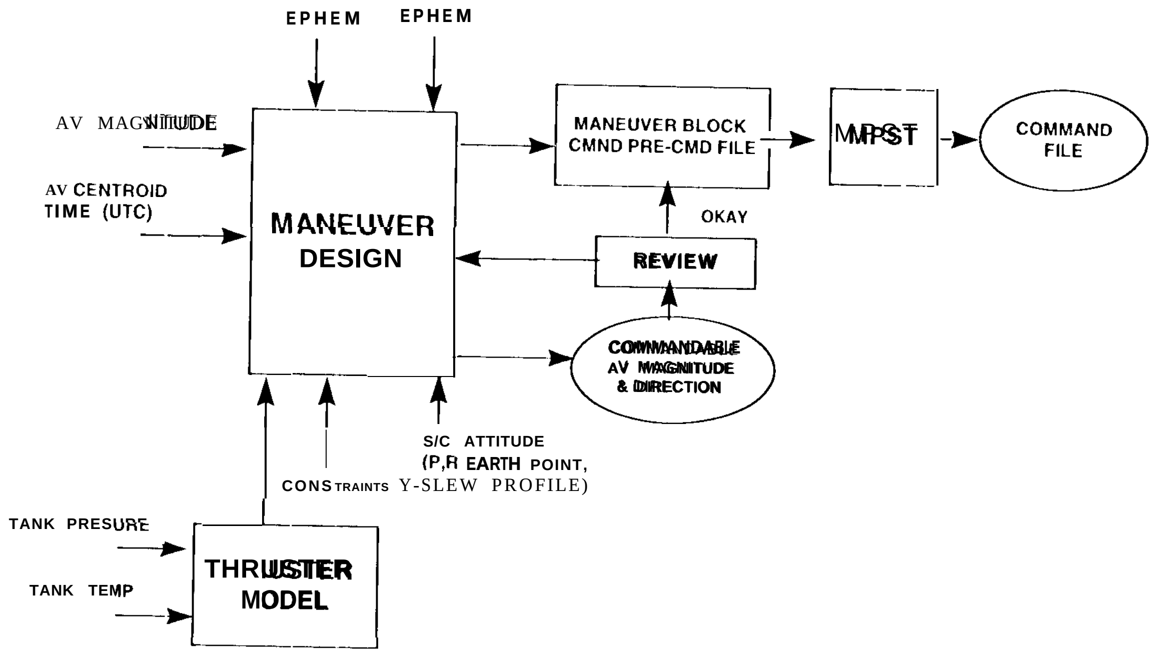

Figure 1 Current TOPEX/Poseidon Maneuver Implementation Design Activity.

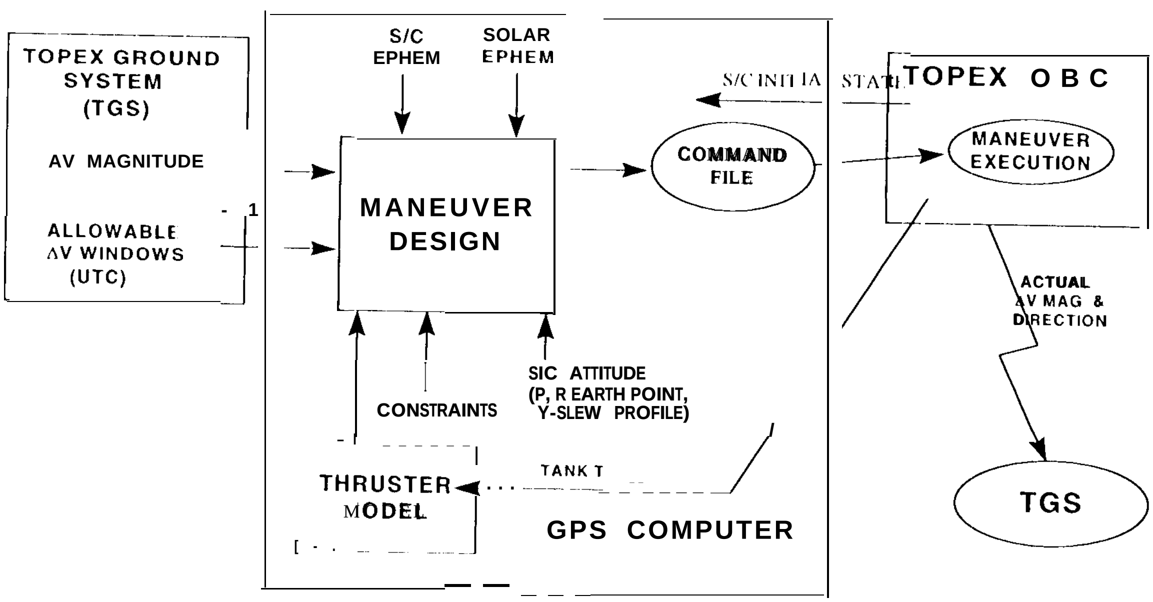

Figure 2 Proposed TOPEX/Poseidon Autonomous Maneuver Implementation.

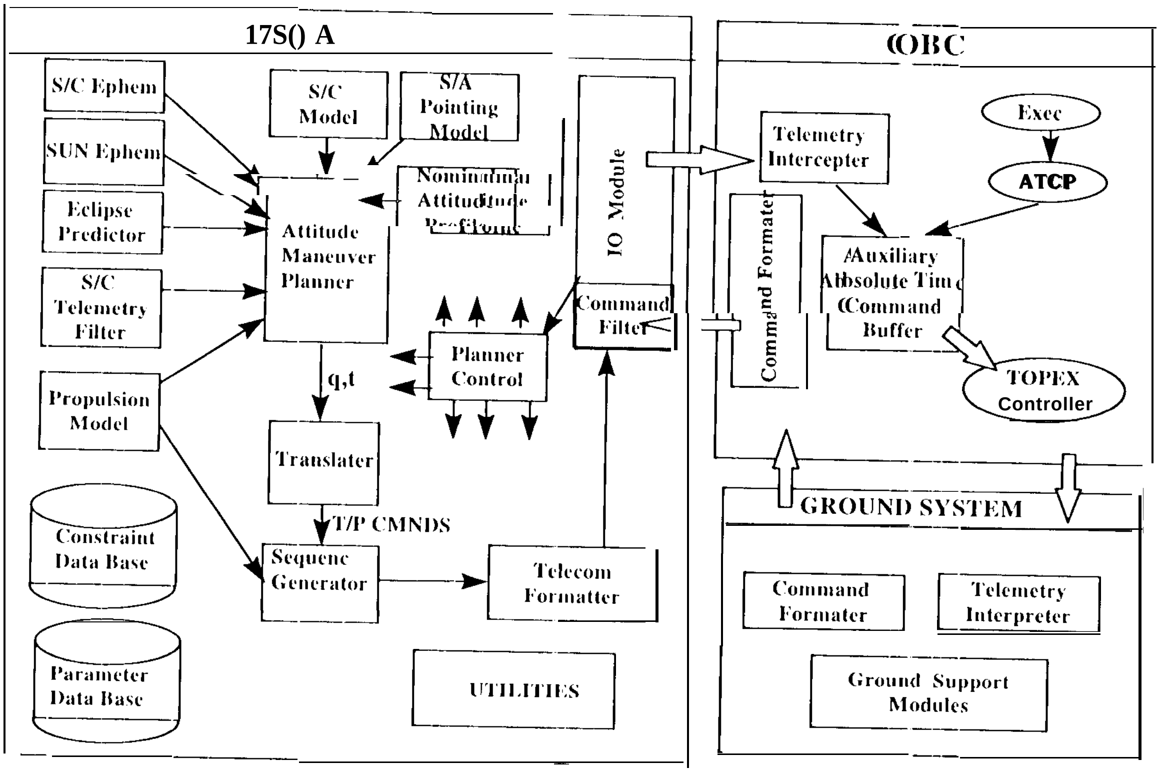

Figure 3 TAME Architecture.

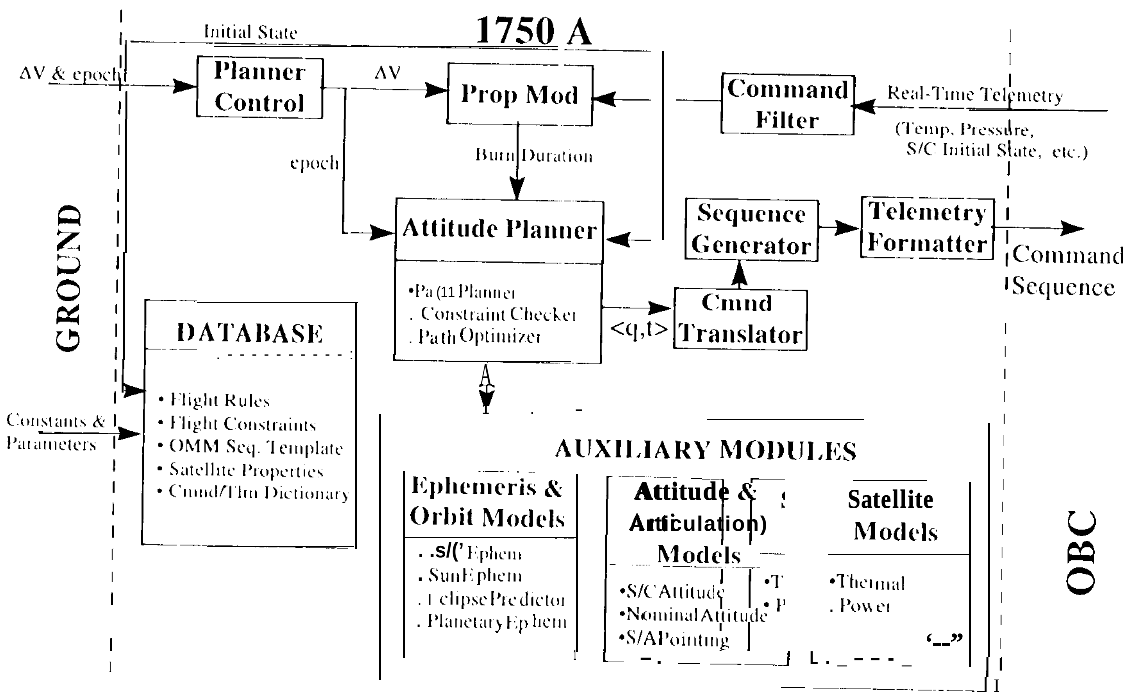

Figure 4 TAME flow diagram

ATTITUDE MANEUVER PLANNER MODULE

The maneuver planning module processes requests for orbit maintenance maneuvers (OMM) and generates spacecraft commands for maneuver execution. An OMM modifies the orbit characteristics for drag make-up. OMMs are accomplished by pointing the spacecraft thruster in the direction of the requested impulse. A maneuver consists of the following:

(1) turns to accomplish the requested pointing
(2) an orbital change propulsive burn at constant attitude,
(3) turns to re-acquire a nominal spacecraft attitude.

The maneuver planning module ensures that all spacecraft pointing constraints are satisfied during the maneuver turns and burns. The maneuver planning module *a priori* computes a maneuver which

(1) acquires the requested attitude at the requested epoch
(2) satisfies all active pointing constraints
(3) includes the spacecraft dynamic behavior
(4) includes settling times
(5) includes turn rate limits

TAME planner creates non-constrained paths by selecting an intermediate attitude point, between the maneuver start anti another point between the OMM epoch and the epoch to the maneuver stop points, Figure 5. in particular, the TAME search routine begins its search for the intermediate point on the boundary of the prime constraint. TAME Maneuver Planner, Figure 6, consists of three main functions:

(1) initialization search
(2) path analysis and optimization.
(3) maneuver profile generation

The Path initializer searches for a set of maneuver profiles that satisfies the prime constraint. '1'0 limit the number of generated attitude commands, Path analyzer analyzes these profiles against constraints listed in the Constraint Table, anti selects the profile that provides the time-optimal attitude maneuver within the selected solution space. The Path Initializer outputs a quaternion/timeline set (maneuver profile) representing a constraint-free maneuver. Finally, the Command Translator converts the maneuver profile to time tagged quaternions to command TOPEX controller.

Attitude Maneuver Planning

The attitude planner's main propose is to reorient and align a satellite body-fixed vector (thrust direction) along an inertialy fixed vector, the requested AV direction, see Figure 7. The plan consists of rotating the spacecraft to the desired orientation, performing a thruster(s) bill'11, and rotating the spacecraft to a new orientation to resume normal mission

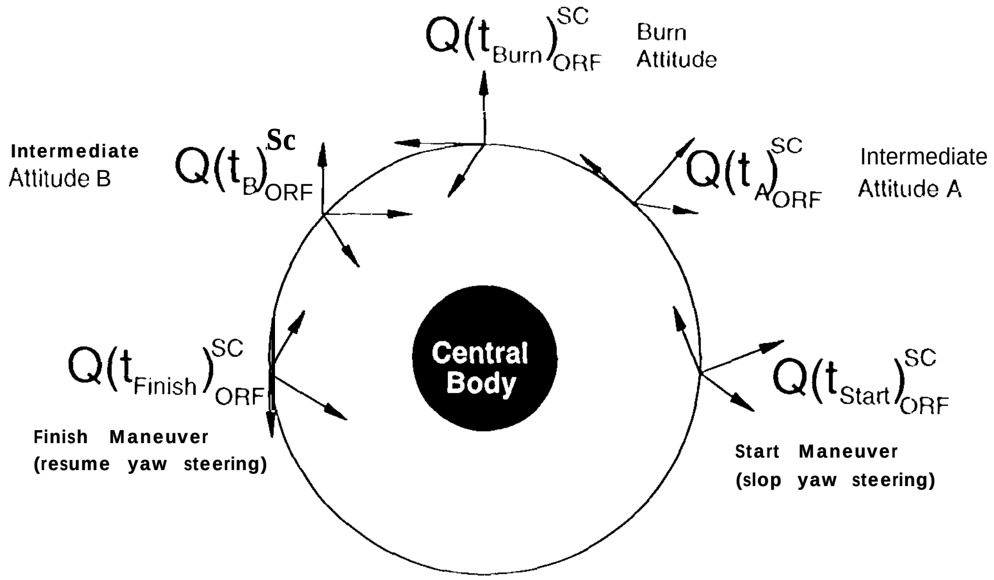

Figure S Maneuver Profile Defined By Attitude Quaternions

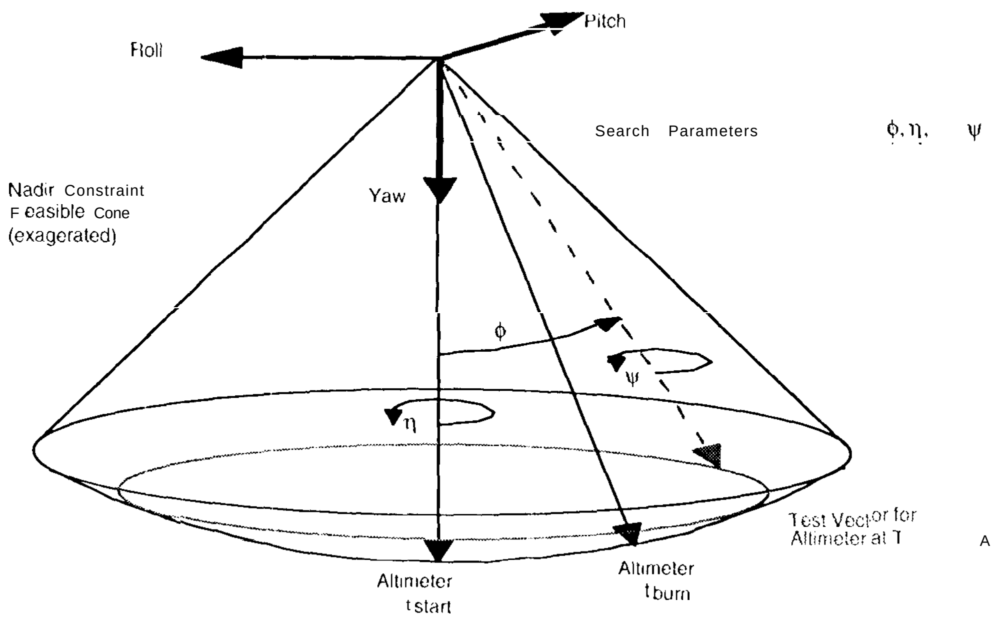

Figure 6 TAME Search Algorithm

activities. The basic maneuver component is a constant eigenaxis rotation with respect to an inertial frame. A turn begins from an initial stationary attitude, continues with spin-up to a constant rotation rate about a single eigenaxis, and ends with spin-clown to a new stationary attitude, Figure 8. Thus all spacecraft body-fixed vectors generate a cone trajectory about the eigenaxis, while inertial vectors remain stationary. The magnitude of the spin vector, $\vec{\omega}$, or *turn rate* is a function Of the spacecraft controller turn characteristic. A typical turn rate curve characteristic, shown in Figure 8, consists of a ramp during spin-up, a constant turn rate during coast, and a negative ramp during spin-down.

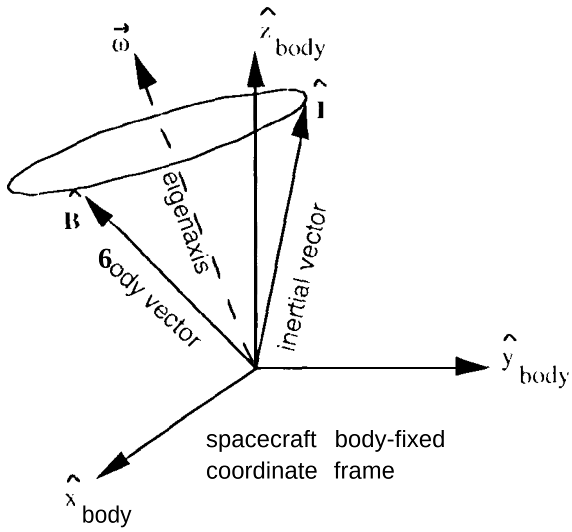

Figure 7. Eigenaxis Turn With Respect to an Inertial Frame (for simplicity the rotations of the body coordinate axes are not shown)

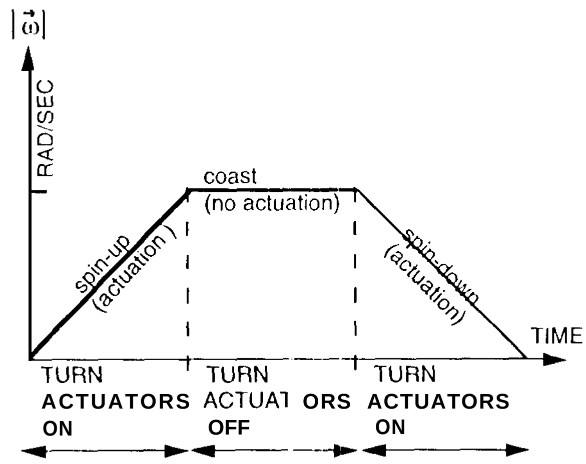

Figure 8. Typical Turn Rate Characteristic

CONSTRAINTS

All maneuvers are subject to pointing and timing constraints. TAME models the pointing constraints as the association between a pair of vectors: a body-fixed vector and all inertially fixed or orbitally fixed vector (Figure 9). A constraint is violated if the body-fixed vector is within a specified angular distance, or half-cone angle, of the inertially fixed vector. Two constraints are illustrated in Figure 10; each constraint pair is indicated by an index. 'There is no theoretical limit on the maximum number of constraints.

in TAME all active constraints are stored on-board. A constraint is defined as active if it is required for the next maneuver. The Constraint Table logically has a row for each constraint pair. Each row is in the following format:

- Body unit vector in body coordinates, dimensionless
- Constraint unit vector in orbital or inertial frame coordinates, dimensionless
- Half-cone angle, radians

in addition to the constraints listed in the table below, TAME maintains a constraint limit on the attitude turn rate in order to manage the satellite stored momentum during the maneuver.

Constraint Type	Body Vector	Constraint Vector	Constraint Angle (deg)	Constraint Time (sec)	Decay Slope
Geom, ORF	Altimeter	Nadir	175	n/a	n/a
Geom, OPF	Star Trkr 1A	Sun	15	n/a	n/a
Geom, OPF	Star Trkr 2A	Sun	15	n/a	n/a
Thermal	+Y	Sun	n/a	n/a	n/a
Power	S.A. 1101111:11	Sun	n/a	n/a	n/a

TABLE 1 TAME constraint table

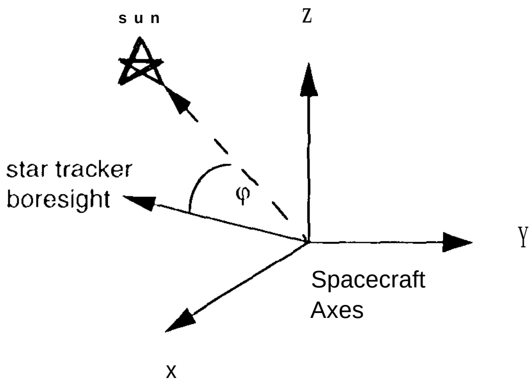

Figure 9 Typical Constraint: Sun Does Not Lie in Star Tracker Field of View(φ).

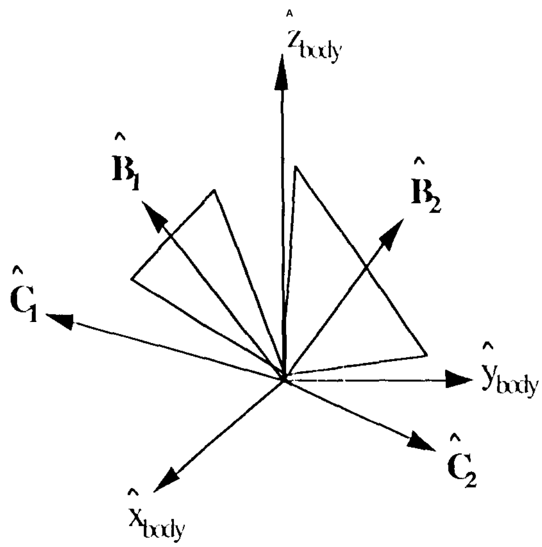

Figure 10 Two Active Constraints

Path Initialization

An admissible maneuver path consists of the sequence of eigenaxis turns, sufficient to align the appropriate body vector with the requested inertial vector; while avoiding ail the constraints specified in the Constraint Table. Figure 11 depicts the TAME path search algorithm The procedure to find the initial path is as follows:

1. Search parameters ϕ and η move the altimeter through a circle in the feasible cone, SCC figure 6.
2. ψ is a rotation about the altimeter.
3. Intermediate attitude $Q(t_A)$ is specified by the 3 euler angles ϕ, η, and ψ.

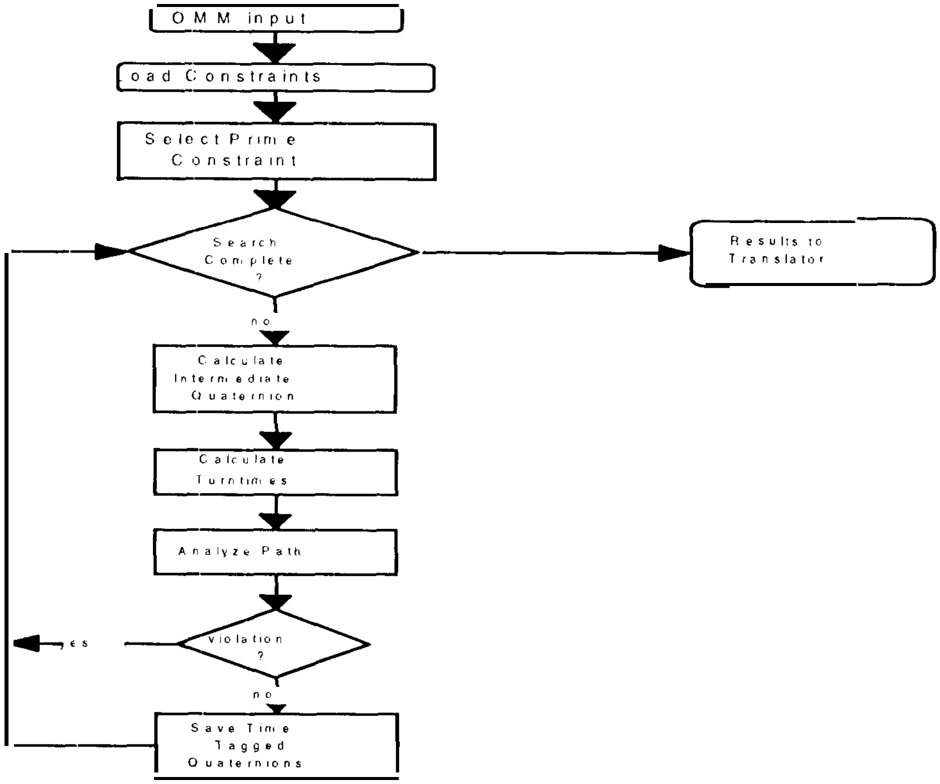

Figure 11 TAME Maneuver Planner Flow diagram

COMMAND TRANSLATER MODULE

The planner output, a stream of time-tagged quaternions, then will pass through a translator that converts them to TOPEX like commands before passing to the sequence generator module. This step is necessary as the TOPEX attitude commander, EulerC, does not have the capability to provide eigenaxis turns. commands about other axes may be applied as biases only.

SEQUENCE GENERATOR MODULE

The sequence generator module creates an OMM equivalent sequence by addiing commands to condition the hardware and software satellite configuration prior to the maneuver execution. This module also adds post maneuver cleanup commands to reconfigure the satellite configuration to its nominal conditions. The generated sequence will then be transmitted to the OBC for execution.

DATA TRANSFER MODULES

Providing means of transferring data between OBC and the 1750A, provided another challenge to the TAME design. Communication between the two computers is based on the existing TOPEX command and telemetry architecture. The 1750A output data is normally slated for transfer to ground as pall of the spacecraft telemetry. In this experiment, the OBC will capture, interpret and verify the telemetry from the 1750A before interleaving it with the existing background commands. The sequence is then stored in the TOPEX absolute **time** command buffer for execution. This will complete the TAME maneuver implementat ion phase. TAME does not change the maneuver executi on phase. Figure 12 graphically shows (hc proposed data transfer architecture.

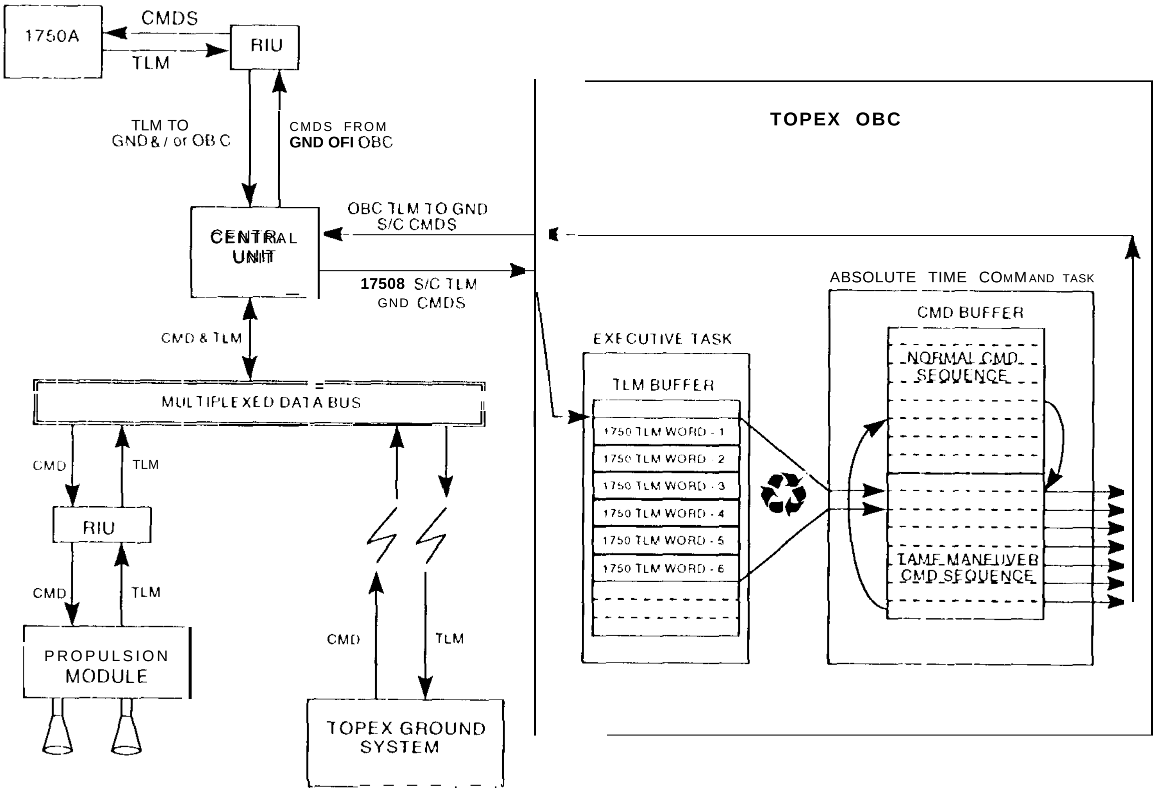

Figure 12 TAME OBC/1750A data transfer architecture

AUXILIARY MODULES

Auxiliary modules have been divided into three different categories:

- **Ephemeris and orbit models** consists of modules that propagate spacecraft and the Sun ephemerides and an eclipse predictor to account for the lack of Sun energy in the thermal and power models.
- **Attitude and Articulation Models** consist of the modules that predict Solar Array pointing, satellite nominal attitude and a satellite attitude model. The satellite attit ude model incl udes the transformation between tile eigenaxis turns and the TOPEX (yaw-axis, bias) turns.
- Satellite models consist of the **thermal ancl power models. These** models are highly specialized and simplified to generate prediction for the highest likely

offender only. As an example the Thermal model predicts the temperature at a single point on the satellite while the power only predicts the battery's depth-of-discharge factor.

PROPULSION MODULE

Propulsion model calculates the desired burn duration for the requested AV magnitude. This module requires an up-lo-date tank temperature that it will query from the OBC.

DATBASE MODULES

The database module is the primary depository of all parameter values needed for the design of the OMM. The database includes:

- Flight Rules and Constraints including thresholds
- OMM sequence template.
- Satellites' properties such as mass, inertias etc.
- Command and telemetry dictionary.

1750A SOFTWARE ARCHITECTURE

On-board the spacecraft, the autonomy software resides in a 1750A computer that, for the purposes of the experiment, acts as a co-processor to the Onboard Computer (OBC). The 1750A computer performs all the calculations for planning the requested maneuver and generates a complete sequence to implement the planned maneuver. The OBC receives anti stores the maneuver sequence of absolute timed commands from the 1 750A. The sequence is then interpreted and executed.

The software on the 1750A computer is substantially original. While it was developed specifically for the TAME experiment, the underlying SW architecture and CMD and TLM interfaces were inherited from the pre-TAME application. The SW on the OBC, on the other hand, is substantially unchanged. A patch was made to the existing SW to accommodate an interactive interface with the 1 750A, to receive and process a sequence generated by the 1750A, and allow detailed ground control of the execution of the autonomously generated sequence.

The inherited architecture of the 1750A software consists of a *main* routine that performs all the application initialization and spawns two processes referred to as the *high* and *low priority loops. This is shown* in figure 13. Not shown in figure 13, but part of the inherited architecture, are two interrupt service routines (ISR) which handle the command and telemetry buffers, and the boot function that resides in ROM. The boot function handles loading the application SW, and the control transfer to the application. A command/telemetry interface supporting these functions, and some basic health check tests are also included but not shown.

As mentioned earlier, the command and telemetry buffers are managed by interrupt service routines. These routines are invoked by hardware interrupts. The commands arc interpreted 111 the high priority loop and the bulk Of the TAME processing occurs in the low priority imp. Interprocess communication is achieved through common data pools and global flags. This method for interprocess communication was also inherited.

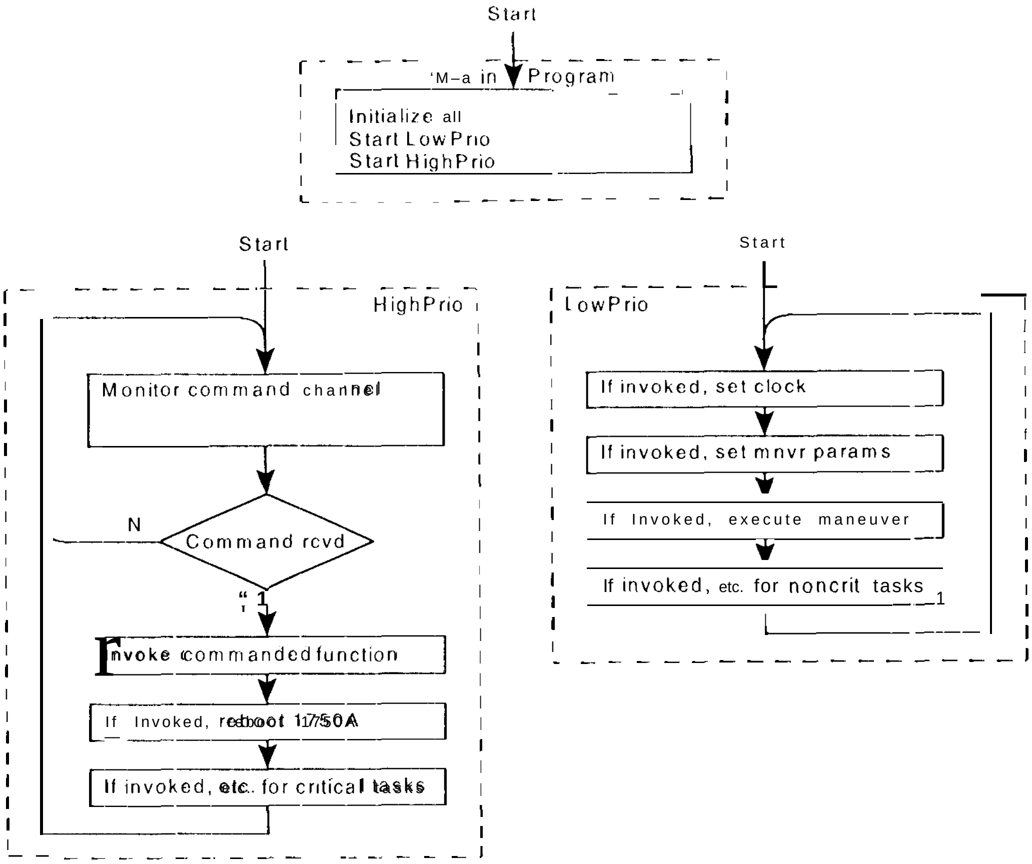

Figure 13 TAME 1750A Software Architecture

EXPERIMENT TEST AND VERIFICATION PLAN

The integration and test of the TAME system follows, and is driven by, the design and implementation process. Therefore, before discussing the I&T process in detail, this section will discuss the TAME design and implementation process and how it influenced the test process.

At a very high level the development can be broken down into 4 elements. These are

- TAME Algorithm Development,
- TAME Flight SW Implementation,
- Embedded System (1750A) Development, and
- OBC SW Development.

Each step is discussed in more detail below.

The TAME function, planning a constraint free attitude trajectory and creating a maneuver sequence, was originally developed in two environments. It was developed partially in MATLAB and partially in FORTRAN. FORTRAN was used wherever existing functions were deemed suitable for reuse. This occurred, for example, in the case of orbit models. New functions were implemen ted in MATLAB.

For the flight implementation, the algorithms were transcribed to ADA and tested on a VAX workstation. TAME Functional testing was also done in the MATLAB environment as part of the algorithm development process.

The software 011 the embedded system is a synthesis of code from tWO sources. The fundamental software architecture, interprocess comm unications, and external interfaces are substantially inherited. These functions are culled from the previous application code and tested in a stand-alone fashion on a 1750 target computer. The second component is the TAME Flight SW. This software, which is based on the MATLAB and FORTRAN code discussed earlier, is integrated with the inherited software and ported to the 1750.

At each step in the development, realistic test cases are used to verify the functionality of the planning software. These test cases fall into two categories. The first of which emulate previously conducted OMM's by restricting the planning degrees of freedom. The spacecraft attitude is required to stay nadir pointed until just before the burn and the only free variable is the burn epoch. in these test cases, the actual spacecraft telemetry is the "truth set" against which the TAME planning function is evaluated. The other class of functional test cases are those which allow off nadir pointing during the turn to the burn attitude. These test cases take advantage of the TAME attitude planning capability to "walk around" a constraint. The functionality and performance of the TAME SW in these cases is verified by analysis. Figures 14 through 18 show sonic of the results of a typical test case.

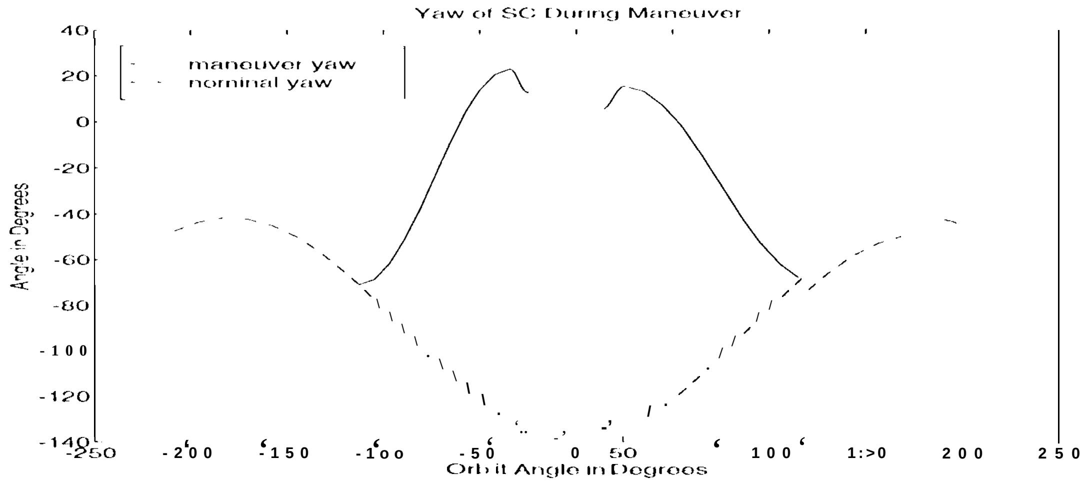

Figure 14 TOPEX Yaw Angle During TAME Maneuver

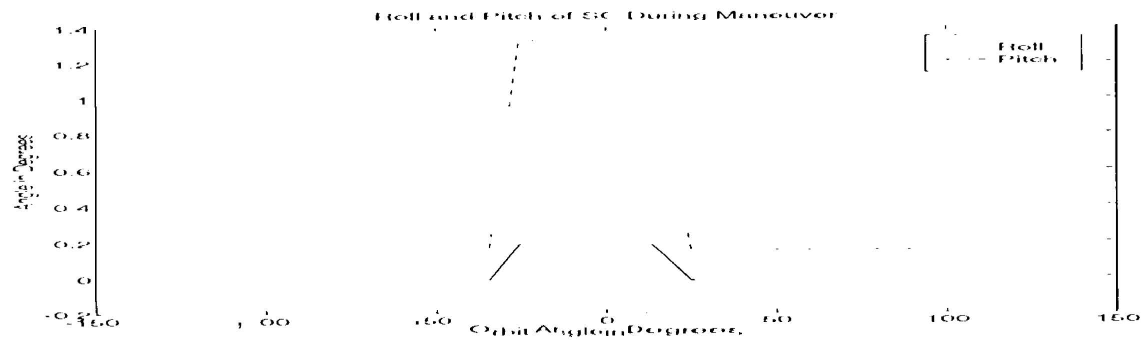

Figure 15 TOPEX Roll and Pitch Angles During TAME Maneuver

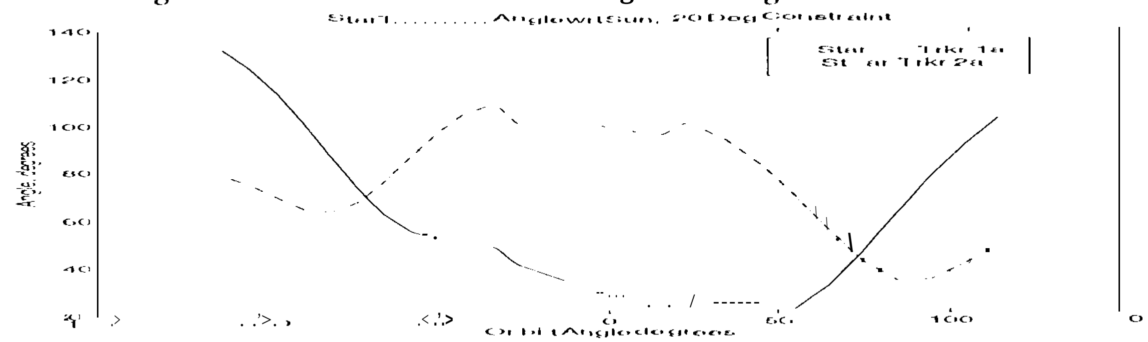

Figure 16 Star Tracker Sun Angles During TAME Maneuver

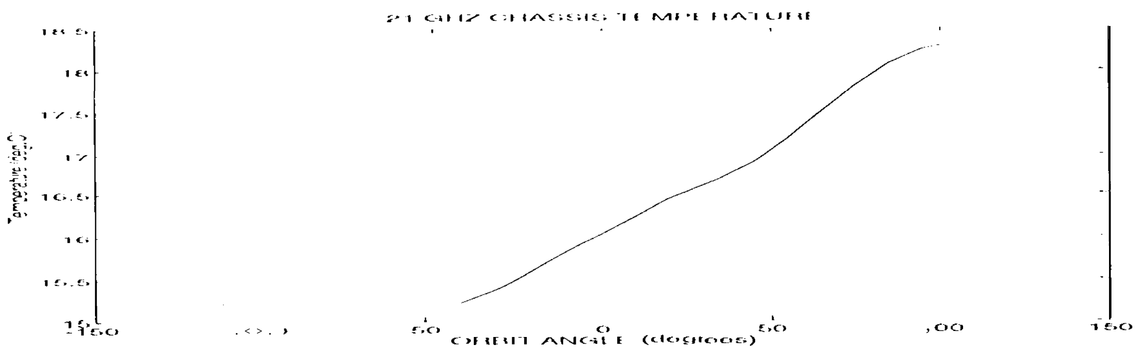

Figure 17 Primary Thermal Constraint During TAME Maneuver

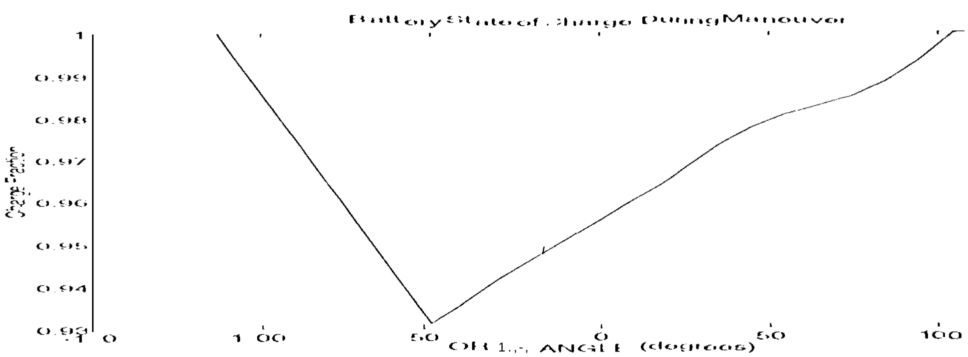

Figure 18 Battery State of Charge During TAME Maneuver

CONCLUSIONS

The feasibility for autonomous propulsive maneuver planning sequence generation was demonstrated in 1994. The 1995 effort generalized the algorithms allowing arbitrary Euler turns in place Of the single axis turns and the code is being written to comply With flight software code requirements. The TOPEX Autonomous Maneuver Experiment (TAME) applies these concepts to a real operational nadir pointed orbiter.

The challenge of the TAME experiment will not be limited to the maneuver planner algorithm. Real mission constraints and oversights would have to be considered for their full impact to ensure a safe experi ment.

ACKNOWLEDGMENTS

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